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Three-dimensional numerical study on turbulent mixed convection in parabolic trough solar receiver tube

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Abstract

The present work focuses on the fully developed mixed turbulent flow and heat transfer in receiver tube heated by non-uniform heat flux, especially the effect of local buoyancy force induced by the non-uniform heat flux at Reynolds number of 2×10^4-10^5, Prandtl number of 1.5 and Grashof number of 0-10^{12}. The friction factor and Nusselt number between forced convection and mixed convection under uniform heat flux and non-uniform heat flux are analyzed quantitatively. The effect of solar elevation angel on the fluid flow and heat transfer is also investigated. We found that it is not feasible to perform the heat transfer design and prediction for parabolic trough solar collector based on the experimental correlations for forced convection or traditional mixed convention.

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Keywords: Parabolic trough solar collector; turbulent mixed convection; non-uniform heat flux; numerical simulation

1. Introduction

Concentrated Solar Power (CSP) has been quickly, with thousands of MW under construction/planning in many parts of the world. The CSP with parabolic trough collector (PTC) is the most proven solar technology compared with linear Fresnel, solar tower and solar dish systems. The fluid flow and heat transfer characteristics in the receiver tube of PTC have a great effect on heat collecting efficiency, which is different from the forced or mixed turbulent flow and heat transfer in circular tube heated by uniform heat flux (UHF) or uniform temperature. The turbulent flow in the parabolic trough receiver (PTR) tube is generally imposed by non-uniform heat flux (NUHF) [1-3]. Although many numerical studies on the three dimensional mixed turbulent flow and heat transfer in receiver tube under

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non-uniform heat flux (NUHF) are investigated [4-5], the effect of natural convection induced by NUHF on turbulent flow and heat transfer has not been analyzed.

The work focuses on the fully developed mixed turbulent flow and heat transfer in receiver tube heated by non-uniform heat flux (NUHF), especially the effect of local buoyancy force induced by the non-uniform heat flux (NUHF). The friction factor f and Nusselt number Nu between forced convection and mixed convection under uniform heat flux (UHF) and non-uniform heat flux (NUHF) are analyzed quantitatively.

2. Model descriptions

The physical model is based on LS-2 parabolic trough solar collector which has been widely used in Solar Energy Generating Systems (SEGS) [6] (Fig.1(a)). We focus on the fully developed mixed turbulent flow and heat transfer of super-heated steam in the circular tube while neglecting the wall thickness and the convection and radiation heat losses. The Reynolds number (Re) based on the hydrodynamic diameter is 2×10^4-10^5 and the Prandtl number is 1.5. The Boussinesq approximation is adopted and the Grashof number (Gr) based on the hydrodynamic diameter and mean heat flux on the wall ranges from 0-10^{12}. The non-uniform heat flux concentrated is same as the MCRT result computed by He et al. [4] (Fig.1(b)). The rotation angel φ between the central normal of parabola and the horizontal plane is equal to the solar elevation angel.

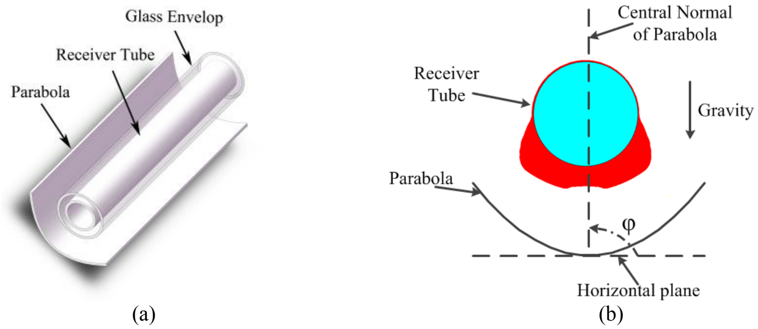


Fig. 1. computational model: (a) schematic of LS-2 parabolic trough solar collector; (b) the profile of non-uniform heat flux on the tube wall

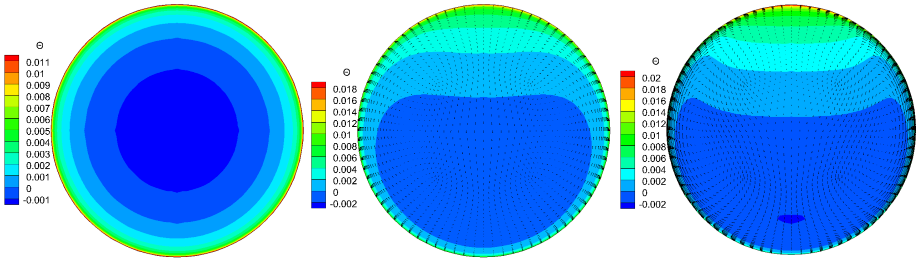
The present research is based on the ANSYS FLUENT software. The governing equations are all discretized by the finite volume method. The SST $k-\omega$ turbulence model is adopted. The convective terms in momentum, k and ω equations are discretized by the second-order upwind scheme, while QUICK scheme is used to discretize the convective terms in energy equation. The pressure is discretized by the scheme of PRESTO!. The SIMPLEC algorithm is used to solve the discretized governing equations. The streamwise periodic boundary condition is realized by user defined function (UDF).

3. Results and discussion

The present numerical results are grid-independent. The computational model is validated by the forced turbulent results from Filonenko formula and Gnielinski formula, in which the deviations are less than 5.3% and 7.4% for friction factor and Nusselt number, respectively.

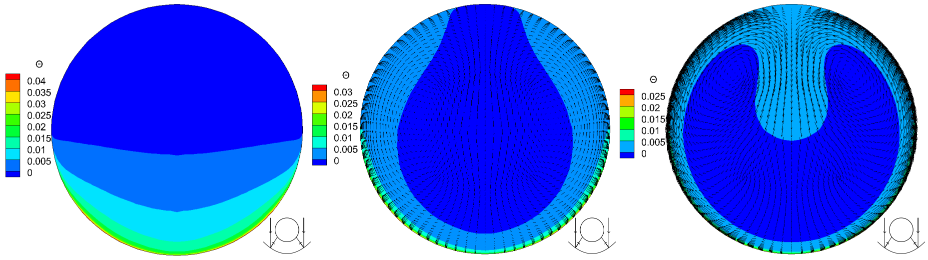
Fig. 2-4 shows the secondary flow and non-dimensional temperature field on the cross section under UHF, NUHF (φ=90°) and NUHF (φ=0°), respectively. It is obvious that there are significant difference in flow field and temperature distribution between UHF and NUHF (see Fig.3 or 4), which will result in different flow resistance and heat transfer rate. Generally, the intensity of secondary flow increases with

Gr increasing. For UHF condition, fluid flows upward along tube wall, so the non-dimensional temperature in top region becomes larger and that in other regions is smaller. For NUHF condition, the secondary flow and temperature distribution are different with different solar elevation angel because of the local non-uniformity of heat flux on the tube wall which will result in locally non-uniform buoyancy force. The differences in flow and temperature field between φ=90° (bottom heated) and φ=0° (left-side heated) are evident.



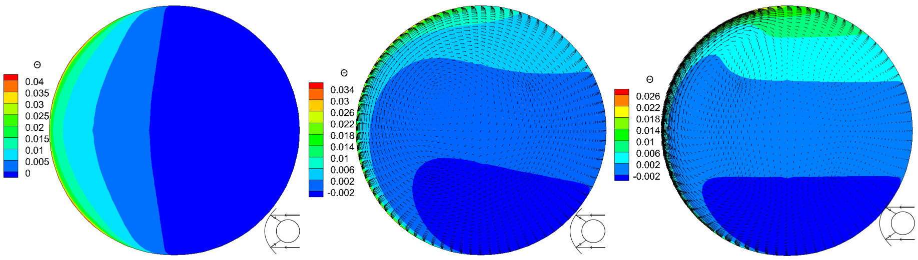
(a) (b) (c)

Fig. 2. secondary flow and non-dimensional temperature field under UHF: (a) Gr=0; (b) Gr=10^9; (c) Gr=10^{10}



(a) (b) (c)

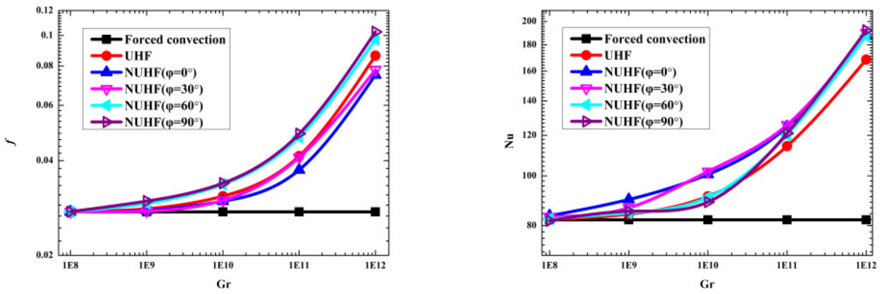
Fig. 3. secondary flow and non-dimensional temperature field under NUHF(φ=90°): (a) Gr=0; (b) Gr=10^9; (c) Gr=10^{10}



(a) (b) (c)

Fig. 4. secondary flow and non-dimensional temperature field under NUHF(φ=0°): (a) Gr=0; (b) Gr=10^9; (c) Gr=10^{10}

As mentioned above, secondary flow induced by buoyancy force will result in lager flow resistance and heat transfer rate, which can be seen from Fig.5 showing the friction factor and Nusselt number of mixed convection. Obviously, the friction factor and Nusselt number increase with the increase of Gr. At the same Gr, the friction factor of mixed convection under UHF is greater than that under NUHF (φ=0° and 30°), however, lower than that under NUHF (φ=60° and 90°). In most cases, Nusselt number of mixed convection under UHF is lower than that under NUHF. Under NUHF, the heat transfer rates with φ=0° and 30° are higher. At high Gr, the flow resistance and heat transfer rate are much higer than those in forced convention (Gr=0), which must be considerate in PTR design.



(a) (b)

Fig. 5. friction factor and Nusselt number vs. Gr at Re=2×10^4: (a) friction factor; (b) Nusselt number

So, for parabolic trough solar collector or any other applications heated by non-uniform heat flux, it is not feasible to perform the heat transfer design based on the experimental correlations for forced convection or traditional mixed convention. Moreover, it is benefit that decreasing the rotation angel φ can induce the high performance of heat transfer and low flow resistance.

4. Conclusions

A comprehensive numerical study is performed to analyze the fully developed turbulent mixed flow and heat transfer performance in receiver tube of parabolic trough solar collector. The effect of thermal boundary condition under UHF and NUHF with different solar elevation angel (φ=0°, 30°, 60° and 90°) on flow and heat transfer is compared.

The results show that there are significant difference in flow field and temperature distribution between UHF and NUHF. Generally speaking, the natural convection can increase flow resistance and heat transfer rate evidently. In most cases, the friction factor of turbulent mixed convection under UHF is greater than that under NUHF (φ=0° and 30°) and less than that under NUHF (φ=60° and 90°). The Nusselt number of turbulent mixed convection under NUHF is larger than that under UHF, especially under NUHF (φ=0° and 30°). For parabolic trough solar collector or any other applications heated by non-uniform heat flux, it is not feasible to perform the heat transfer design and prediction based on the experimental correlations for forced convection or traditional mixed convention.

Acknowledgements

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Biography

Zeng-Yao Li is Professor at School of Energy and Power Engineering, Xi'an Jiaotong University. His researches cover thermal management in energy system, numerical prediction approaches for fluid flow and heat transfer and multiscale transport phenomena.

Biography

Zhen Huang is a PHD student at School of Energy and Power Engineering, Xi'an Jiaotong University. His main research interests are mixed convection and heat transfer enhancement in receiver tube of parabolic trough solar collector.